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Procedia Computer Science 83 (2016) 832 – 838

Procedia Computer Science

The 6th International Conference on Sustainable Energy Information Technology (SEIT 2016)

Study of voltage fluctuations caused in a distribution grid by the connection of a wave energy converter and corrective actions based on reactive power compensation

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Abstract

Renewable energies, in general, have considerably increased their penetration in electrical power systems. However, they are intermittent energy sources, and large amounts of this power could create problems for the proper operation of the electrical network. In this sense, this paper studies the effects of wave energy generation on the voltages in a distribution network, using the IEEE 34-bus test feeder. In addition, corrective actions based on reactive power compensation, such as reactive compensation from the grid-side converter of the wave energy converter and the use of a STATCOM, are presented. The results show that the use of the grid-side converter as a reactive power compensator improves the voltage quality in the network, although its capability to mitigate voltage fluctuations is limited. The use of a complementary external STATCOM can provide for extra compensation if needed.

Peer-review under responsibility of the Conference Program Chairs
Keywords: Reactive power compensation; voltage fluctuation; wave energy.

1. Introduction

Oceans represent a huge renewable energy resource in different forms: wind, tides, streams, salinity or thermal gradients, and waves. In the case of the exploitation of wave energy for electricity generation, many different technologies have been proposed, being under the whole range of technology readiness levels [1,2]. In these Wave Energy Converters (WEC), the energy conversion is carried out in two main steps. In the first one, the oscillating movement of water particles is transformed into the movement of a body or a work fluid by means of a mechanical device. A secondary conversion, from mechanical to electrical energy, is then performed by the so called Power Take Off (PTO) system. The irregular and oscillating character of ocean waves, with 10 s being the order of magnitude of the period of the most energetic ones, turns into an irregular and oscillating electrical power production, typically with half the

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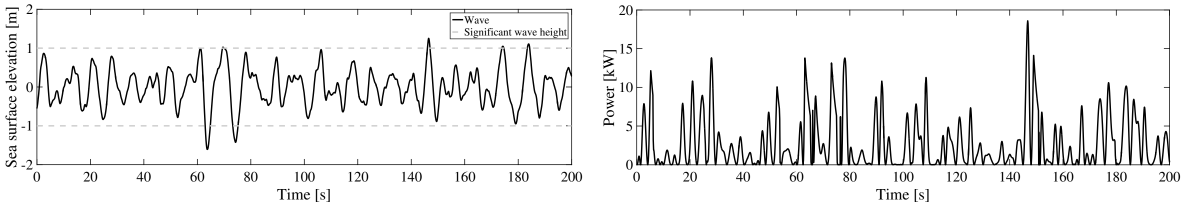
Peer-review under responsibility of the Conference Program Chairs
doi:10.1016/j.procs.2016.04.173

wave period. For example, Fig. 1 (a) shows the sea surface elevation as a function of time at a given location for a group of waves with significant height of 2 m and a peak period of 8 s, and Fig. 1 (b) shows the corresponding electrical power production of a WEC placed in that location[3].



(a) Incoming wave. (b) Electrical power generated by a WEC.

Fig. 1: Wave and electrical power profiles.

When the power production of the WEC is injected into the grid, it causes a variation of the voltage at the connection point. The variability of the active power depends on the sea state and, also, on the existence of some kind of energy buffering between the conversion steps. WECs with direct driven generators, such as the one whose power production is shown in Fig. 1 (b), present the highest variability for a given sea state. These power variations are the cause of voltage fluctuations and flicker in grid buses close to the connection point[4]. To mitigate these effects, the use of STATCOMs has been shown as an interesting option[5].

This paper presents a study of the voltage fluctuations in a test ac distribution network caused by the active power injection from a WEC and the analysis of some corrective actions based on reactive power injection from the WEC itself and from additional reactive compensation equipment.

2. Voltage fluctuations in a test network caused by the connection of a wave energy converter

2.1. Test network

The test network used in this study is based on the IEEE 34-bus test feeder[6], an actual feeder with a nominal voltage of 24.9 kV, whose one-line diagram is shown in Fig. 2, with the following modifications:

- Regulators are not considered
- Distributed loads are considered as spot loads connected at the farthest point from bus 800
- Unbalanced loads are converted to balanced ones by connecting the higher load in each phase
- Single-phase lines and loads are taken as three-phase ones
- All loads are treated as constant power
- Capacitor banks are disconnected
- The grid beyond bus 800 is modeled as an infinite bus behind a transformer

The details on the electrical parameters that model the test network can be found in Appendix A.

For the given network topology and for a given voltage at the infinite bus, it is possible to determine the voltage at the different buses of the network as a function of the power injected by the WEC in bus 890 by means of a power flow. The infinite bus is the slack bus and all the other buses, including bus 890, are treated as PQ buses. For example, by using a Gauss-Seidel recursive algorithm, the voltage phasor at bus i in the m-th iteration can be expressed as:

$$\underline{U}_i^{(m)} = \frac{1}{\underline{Y}_{ii}} \left[-\frac{P_i - jQ_i}{\left(\underline{U}_i^{(m-1)}\right)^*} - \sum_{k=2}^{i-1} \underline{Y}_{ik} \underline{U}_k^{(m)} - \sum_{k=i+1}^{35} \underline{Y}_{ik} \underline{U}_k^{(m-1)} \right] \tag{1}$$

where: $\underline{Y}_{ik}$ is the i-k element of the nodal complex admittance matrix, P_i and Q_i are the active and reactive power demand at bus i, and the asterisk denotes the complex conjugate.

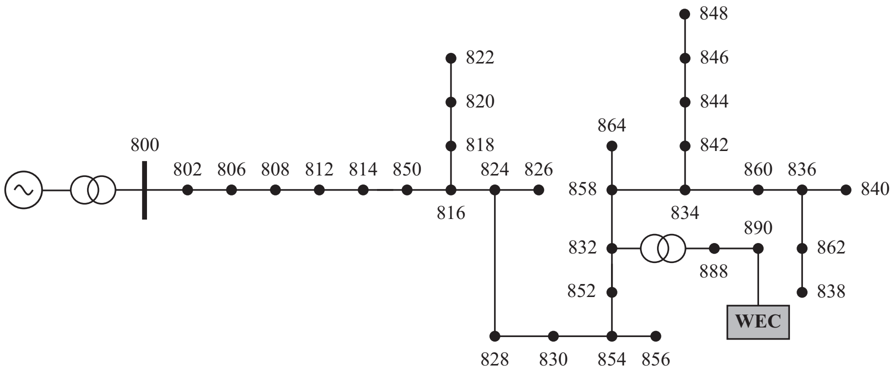


Fig. 2: Modified IEEE 34-bus test feeder[6].

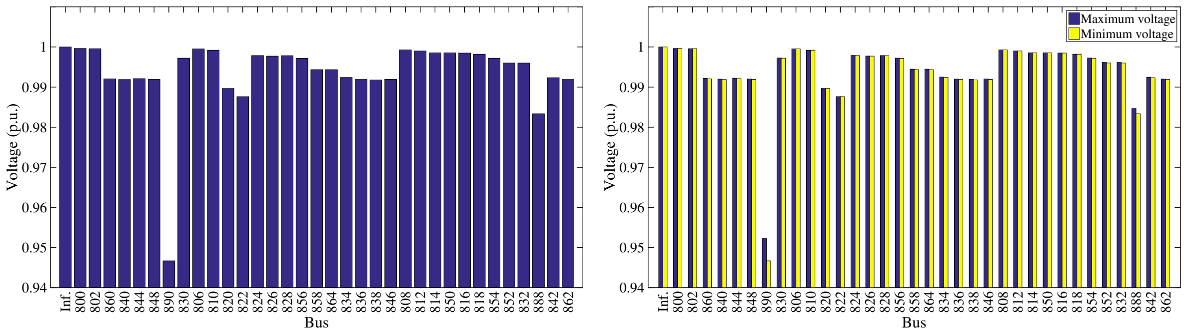
2.2. Network voltage profiles

For a situation with zero power production from the WEC, Fig. 3 (a) shows the network voltage profile in per unit (p.u.) of the voltage at the infinite bus. As the connection point ($i = 8$) coincides with a bus with a high active and reactive power demand, the bus voltage is low ($U_8 = 0.947$ p.u.).

To illustrate the voltage fluctuations caused by the oscillating power injection from the WEC when it is online, let us first consider the power production in an ideal sea state with regular waves, for example, a pure sinusoidal time evolution of the active power injected by the WEC, ranging from zero to P_{max} with a period of T_p, i.e.:

$$P_{WEC}(t) = \frac{1}{2} P_{max} \left[1 - \cos\left(\frac{2\pi}{T_p} \cdot t \right) \right] \tag{2}$$

For a given time instant, t, the voltage values at each bus of the network can be recursively calculated by entering $P_8 = -P_{WEC}(t)$ in equation 1. For example, Fig. 3 (b) shows the maximum and minimum voltage values at each bus from a sweep over a complete P_{WEC} cycle with: $P_{max} = 25$ kW, $T_p = 10$ s, and unity power factor.



(a) (b)

Fig. 3: (a) Network voltage profile of the test network without WEC. (b) Maximum and minimum values of voltages for a sinusoidal power injection from the WEC (equation 2) with $P_{max} = 25$ kW, $T_p = 10$ s, and unity power factor ($Q_8 = 0$).

3. Corrective actions based on reactive power compensation

Different corrective actions can be taken to address the problem of the induced voltage fluctuations, based on diverse approaches[4,7]: use of energy storage to smooth power fluctuations, design of an appropriate spatial configuration of the array of WECs in a farm, implementation of control strategies to maximize fluctuation cancellation, grid reinforcement for increasing short-circuit power, or reactive power compensation. Based on the latter, this work analyzes the exploitation of the reactive power capability of the grid-side electronic converter of the own WEC to compensate for voltage fluctuations. The reactive power injection from a complementary external STATCOM is also studied.

3.1. Reactive compensation from the grid-side converter of the WEC

Direct driven generators are connected to the grid through a power electronics converter. Apart from the capability of transferring the generated power from the electric generator to the grid, this converter, particularly its grid-side part, is able to interchange (generate or absorb) reactive power with the grid. Generally, the reactive capability limits depend on the active power delivered by the converter, as the case shown in Fig. 4 (a) for the WEC under study.

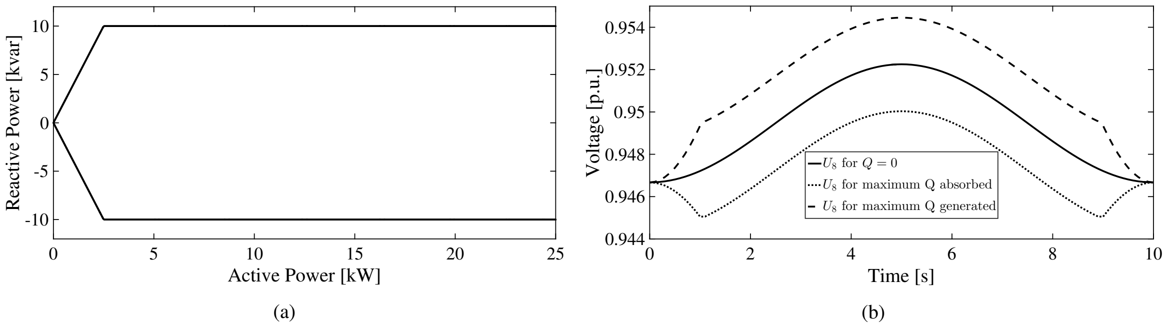


Fig. 4: (a) Active-reactive power operational limits of the grid-side electronic converter of the WEC. (b) Voltage fluctuation at bus 890.

Taking into account the different reactive operating points available for a given value of the active power, it is possible to act on the voltage to a certain limit, for example, with the aim of minimizing voltage fluctuations. Fig. 4 (b) shows the evolution of voltage at bus 890 for the regular power profile defined in section 2.2, for three different cases: maximum, minimum, and zero reactive power injection. The area between the upper and the lower curve represents all possible voltage values attainable with an adequate control of the reactive power injected by the converter.

A more realistic power profile results from considering that real waves are irregular. For example, for the active power profile shown in the upper part of Fig. 5 (a), the lower part of the figure shows the evolution of voltage at three different buses, with no reactive power injection. Obviously, the proximity to the infinite bus, or the distance from the WEC, mitigate the amplitude of voltage fluctuations.

Fig. 5 (b) illustrates the case when the reactive capabilities of the WEC grid-side converter are used. A simple PI controller has been tested to keep the voltage at the WEC connection point at a given set-point, U_8^{sp}. The upper part of the figure shows the evolution of this voltage and the injected reactive power. The lower part of the figure shows the evolution of voltage at the same three buses as Fig. 5 (a). It can be seen that voltage fluctuations can be filtered for lower values of active power. However, for higher values, this is no longer possible because there are not enough reactive resources available from the WEC power electronics converter.

3.2. Complementary reactive compensation from an external STATCOM

If further voltage fluctuation mitigation is needed, additional reactive compensation equipment can be used. Fig. 6 (a) illustrates the use of a STATCOM connected in parallel with the WEC at bus 890. The upper part of the figure shows the reactive power injected by the STATCOM ($Q_{statcom}$) along with the voltage at the connection point. The action of the STATCOM reinforces that of the WEC. As in Figs. 5 (a) and 5 (b), the lower part of Fig. 6 (a) represents the voltage evolution in different buses of the network, where the reduction of voltage fluctuations can be noted.

Sometimes, it is not convenient to connect the STATCOM right in parallel with the WEC because of the harsh environmental conditions of the sea. Fig. 6 (b) is similar to Fig. 6 (a), but with the STACOM connected to bus 888 (i = 33).

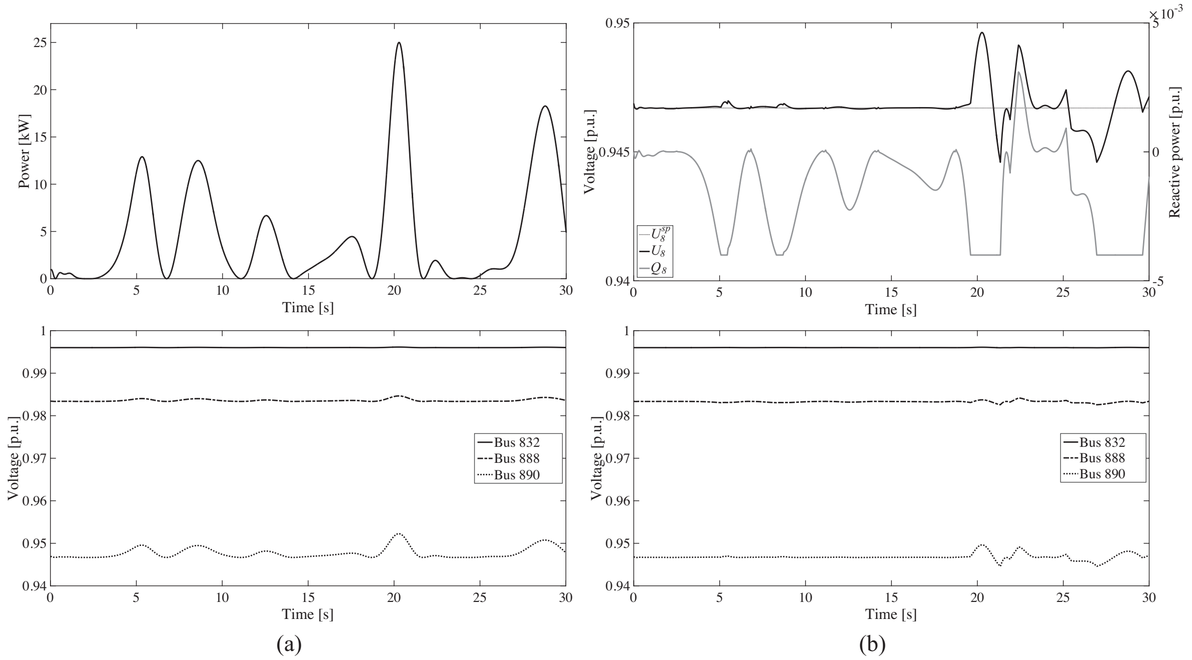


Fig. 5: Voltage fluctuations with irregular waves: (a) with zero reactive power injection, (b) with a controlled reactive power injection from the WEC grid-side converter.

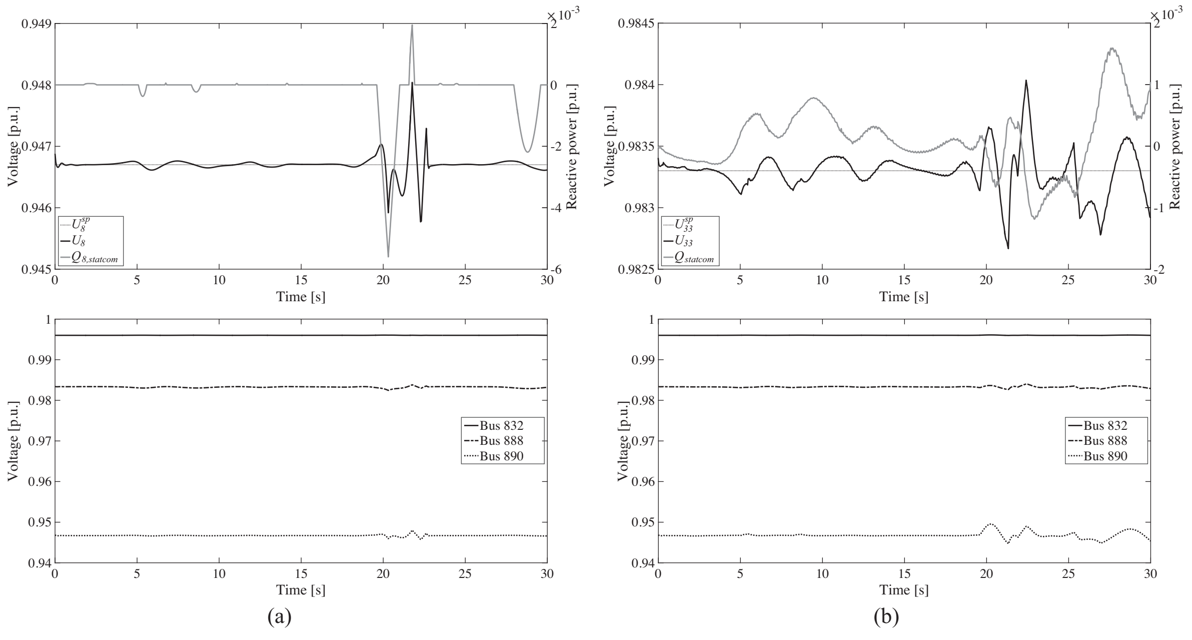


Fig. 6: Voltage fluctuations with irregular waves and a controlled reactive power injection from the WEC grid-side converter and: (a) STATCOM connected to bus 890. (b) STATCOM connected to bus 888.

4. Conclusions

The high variability of the power injected in the electrical grid by wave energy converters may lead to a poor power quality in terms of voltage fluctuations. In this sense, correction actions must be studied and applied to mitigate the disturbances in the grid caused by this intermittent energy resource. This paper studies the voltage fluctuations in the IEEE 34-bus test feeder when connecting a WEC and shows how the WEC grid-side converter can be used to somehow mitigate the voltage fluctuations, without additional investments. However, its application is limited by the PQ capabilities of the converter. In case that additional compensation is needed, extra reactive power can be provided by additional equipment such as a STATCOM.

Acknowledgements

This work was supported in part by CAPES (Brazil), under Grant BEX-9376135, and in part by the Spanish Ministry of Economy and Competitivity under Grant ENE2012-36981.

Appendix A. Electrical parameters of the test network elements

In this appendix, tables A.1, A.2 and A.3 compile the values of the electrical parameters of the different elements in the test network.

Table A.1: Bus parameters.

Bus identifier	Bus index	Active Load (kW)	Reactive load (kvar)	Bus identifier	Bus index	Active Load (kW)	Reactive load (kvar)
Infinite bus	1	0	0	836	21	42	22
800	2	0	0	838	22	28	14
802	3	0	0	840	5	31	18
806	10	30	15	842	34	0	0
808	24	0	0	844	6	144	110
810	11	16	8	846	23	25	12
812	25	0	0	848	7	43	27
814	26	0	0	850	27	0	0
816	28	0	0	852	31	0	0
818	29	0	0	854	30	0	0
820	12	34	17	856	17	4	2
822	13	135	70	858	18	7	3
824	14	5	2	860	4	130	71
826	15	40	20	862	35	0	0
828	16	4	2	864	19	2	1
830	9	17	8	888	33	0	0
832	32	0	0	890	8	150	75
834	20	15	8				

Table A.2: Line parameters.

From bus	To bus	Resistance (Ω/km)	Reactance (Ω/km)	Conductance (S/km)	Susceptance (S/km)	Length (km)
800	802	0.826	0.833	0.000	3.107	0.786
802	806	0.826	0.833	0.000	3.107	0.527
806	808	0.826	0.833	0.000	3.107	9.824
808	810	1.740	0.923	0.000	2.625	1.769

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Table A.2 – *Continued from previous page*

From bus	To bus	Resistance (Ω/km)	Reactance (Ω/km)	Conductance (S/km)	Susceptance (S/km)	Length (km)
808	812	0.826	0.833	0.000	3.107	11.430
812	814	0.826	0.833	0.000	3.107	9.062
814	850	1.193	0.882	0.000	3.045	0.003
816	818	1.740	0.923	0.000	2.625	0.521
816	824	1.193	0.882	0.000	3.045	3.112
818	820	1.740	0.923	0.000	2.625	14.676
820	822	1.740	0.923	0.000	2.625	4.188
824	826	1.740	0.923	0.000	2.625	0.924
824	828	1.193	0.882	0.000	3.045	0.256
828	830	1.193	0.882	0.000	3.045	6.230
830	854	1.193	0.882	0.000	3.045	0.158
832	858	1.193	0.882	0.000	3.045	1.494
834	860	1.193	0.882	0.000	3.045	0.616
834	842	1.193	0.882	0.000	3.045	0.085
836	840	1.193	0.882	0.000	3.045	0.262
836	862	1.193	0.882	0.000	3.045	0.085
842	844	1.193	0.882	0.000	3.045	0.411
844	846	1.193	0.882	0.000	3.045	1.109
846	848	1.193	0.882	0.000	3.045	0.162
850	816	1.193	0.882	0.000	3.045	0.094
852	832	1.193	0.882	0.000	3.045	0.003
854	856	1.740	0.923	0.000	2.625	7.111
854	852	1.193	0.882	0.000	3.447	11.226
858	864	1.740	0.923	0.000	2.625	0.494
858	834	1.193	0.882	0.000	3.045	1.777
860	836	1.193	0.882	0.000	3.045	0.817
862	838	1.194	0.883	0.000	2.711	1.481
888	890	0.826	0.833	0.000	3.107	3.219

Table A.3: Transformer parameters.

Primary bus	Secondary bus	Rated power (kVA)	Primary rated voltage (kV)	Secondary rated voltage (kV)	Short-circuit resistance (%)	Short-circuit reactance (%)
Infinite bus	800	2500	69	24.9	1	8
832	888	500	24.9	4.6	1.9	4.08

References

1. A. d. O. Falcão, Wave energy utilization: A review of the technologies, Renewable and sustainable energy reviews 14 (3) (2010) 899–918.
2. I. López, J. Andreu, S. Ceballos, I. M. de Alegría, I. Kortabarria, Review of wave energy technologies and the necessary power-equipment, Renewable and sustainable energy reviews 27 (2013) 413–434.
3. H. Mendonça, S. Martinez, Modeling of a wave energy converter connected to a resistive load, in: 4th International Youth Conference on Energy (IYCE), IEEE, 2013, pp. 1–6.
4. F. Sharkey, J. MacEnri, E. Bannon, M. Conlon, K. Gaughan, Resource-induced voltage flicker for wave energy converters–assessment tools, IET Renewable Power Generation 7 (6) (2013) 623–630.
5. S. Martinez, J. A. Sanchez, H. Mendonça, R. Alvaro, A. Cuesta, A. Diez, Impact of a wave energy farm connected to a distribution grid in voltage power quality, in: CIGRE, the Council on Large Electric Systems – 2013 Lisbon Symposium, 2013, pp. 1–8.
6. Distribution System Analysis Subcommittee, IEEE 34 node test feeder, `http://ewh.ieee.org/soc/pes/dsacom/testfeeders/`, [Online; accessed 20-January-2016] (2010).
7. M. Lafoz, M. Blanco, D. Ramirez, Grid connection for wave power farms, in: Proceedings of the 14th European Conference on Power Electronics and Applications (EPE 2011), IEEE, 2011, pp. 1–10.